

Initial Operations Experience and Results from the Juno Gravity Experiment

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Abstract—Radio communications between the Juno spacecraft, in orbit around Jupiter, and the Earth-based observing stations of NASA’s Deep Space Network enable measurements of the Doppler shift induced on the radio signals by Juno’s motion in the Jovian environment. This measurement of the Doppler shift improves the knowledge of Jupiter’s gravitational field. As a radio science instrument, Juno’s gravity science instrument utilizes a ground component at the Deep Space Network’s DSS-25 antenna, equipped with simultaneous dual X- and Ka-band transmitters and receivers, and a spacecraft component, which includes X- and Ka-band transponders to relay the transmitted signal back to Earth. Originally planned to be in 14-day orbits around Jupiter, a risk identified in the propulsion system led to the decision to stay in the 53-day orbit period. Rapid turnaround of observation planning led to successful near-term perijove passes. Although maintaining a 53-day orbit period provides a scientific benefit to the gravity science investigation, the longer orbit period further increases the large dynamic range in Doppler shift and pointing angles induced by the geometry of each perijove. Between entering orbit at Jupiter on July 5, 2016 and September 2017, the Juno spacecraft has executed eight closest approach periods every 53 days where science data was collected. The first five perijove passes were conducted in different telecom configurations, each presenting unique challenges in data collection and processing. Perijoves PJ-01, PJ-02, PJ-03, and PJ-06 utilized the high-gain antenna and various configurations of the X- and Ka-bands. Perijoves PJ-04 and PJ-05 utilized the medium-gain antenna at X-band only while the spacecraft was off-Earth point. Additional perijoves are planned every 53-days, with an additional five by March 2018. Lessons learned from operating and collecting data at each perijove are documented and will be utilized in future perijoves. Analysis of the first two gravity science perijoves has improved the precision of Jupiter’s gravity field by a factor of five, providing crucial constraints on the interior structure of Jupiter.

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1. INTRODUCTION

Juno is a National Aeronautics and Space Administration (NASA) New Frontiers mission with goals to learn about Jupiter’s origin. After a five-year interplanetary cruise, on July 4, 2016 the spacecraft executed an orbit insertion burn placing it in a 53-day, highly elliptical polar capture orbit. After two of these orbits, it was planned to execute a period reduction maneuver in October 2016 in order to reduce the period to 14-days. However, due to a risk identified in the propulsion system prior to the burn, the maneuver was cancelled and the decision was made to keep the Juno spacecraft in the 53-day orbit [1].

The Juno mission has five primary science investigations: atmospheric composition, atmospheric structure, magnetic field, gravity field, and polar magnetosphere. A suite of eight science instruments provides the measurements to evaluate these characteristics of Jupiter. The gravity science investigation will determine the gravity field to constrain the mass of the core, probe the centrifugal response of the planet to investigate the deep zonal flow, and investigate the tidal response from Io. To investigate the interior, the gravity science investigation utilizes the X-band telecommunications link and Ka-band Radio Science link between the spacecraft and Earth-based observing stations of NASA’s Deep Space Network (DSN) to measure the Doppler shift caused by the motion of the spacecraft. As the spacecraft flies close to Jupiter during perijove, the signals become sensitive to changes in the gravitational field.

Between entering orbit on July 4, 2016 and September 1, 2017, the Juno spacecraft has executed eight close approaches (perijoves) of Jupiter. All have collected Doppler tracking data in support of the gravity science investigation. This paper describes the data collection efforts the resulting gravity science data at each perijove and summarizes the science results from the first two perijoves.

2. INSTRUMENT OVERVIEW

The Juno Gravity Science Instrument is separated into two components: the spacecraft element, which includes the communications transponders, and the ground element, which includes the transmitters, receivers, and frequency reference. In order to maximize the scientific return of the

Juno gravity observations, the radio science instrument uses dual-frequency links: X-Band and Ka-band. All gravity measurements are conducted in a coherent two-way mode, where the frequency reference is generated at the DSN ground station and transmitted to the spacecraft. The on-board Small Deep Space Transponder (SDST) and Ka-Band Translator (KaT) transponders turn the signal around for reception back at the DSN ground station (Figure 1).

The two frequency bands simultaneously used are:

- A X-band downlink (8404 MHz) coherent with an X-band uplink (7153 MHz)
- A Ka-band downlink (32 GHz) coherent with a Ka-band uplink (34 GHz)

Spacecraft Component

The gravity science experiment makes use of the telecom subsystem and Ka-band Translator (KaT). The telecom subsystem along with the KaT are located within the spacecraft radiation vault designed to protect against a total integrated dose (TID) of 25 krad.

The Telecom subsystem—The telecom subsystem provides the X-band part of the Doppler measurements needed for gravity science. The key components of the telecom subsystem include:

Small Deep Space Transponder (SDST): There are two distinct SDSTs. The prime unit has the capability to provide X-up/X-down and X-up/Ka-down (X-band/Ka-band provided as a backup to the KaT) while the redundant unit has only a single band X-up/X-down. The X-band downlink carrier (8404 MHz) is generated by the SDST by coherently

multiplying the frequency of the uplink carrier (7153 MHz) by the turn-around ratio 880/749 [2].

Traveling Wave Tube Amplifier (TWTa): There are two redundant 25 Watt X-Band TWTAs on Juno. The TWTa is comprised of the traveling wave tube and the electronic power converter [2].

High-Gain Antenna (HGA): The HGA is a 2.5-m dual-band (X and Ka) dual reflector. All nominal X- and Ka-band gravity passes use the HGA [2].

The Ka-band Translator (KaT)—The Ka-band translator is a radio science instrument that is used for Doppler tracking at Jupiter. It receives a Ka-band uplink carrier at 34 GHz and down converts it to the downlink carrier at 32 GHz. The KaT design is based on an advanced signal processing algorithm to enable optimization of carrier acquisition and tracking [4].

Ground Component

The Deep Space Network is a system of antennas used for commanding, tracking, and monitoring about 35 interplanetary missions flown by NASA and other international space agencies. Three complexes, spaced evenly around the Earth at Goldstone, California; Madrid, Spain; and Canberra, Australia provide continuous coverage for these spacecraft as the Earth rotates. Each complex includes one 70-m dish and several 34-m antennas.

Among the 34-m antennas, the beam waveguide (BWG) antennas are the newest and most sophisticated. Namely, the BWGs have a series of mirrors that reflect radio signals from the antenna to a room below the ground. With their highly sensitive electronics housed safely underground, these

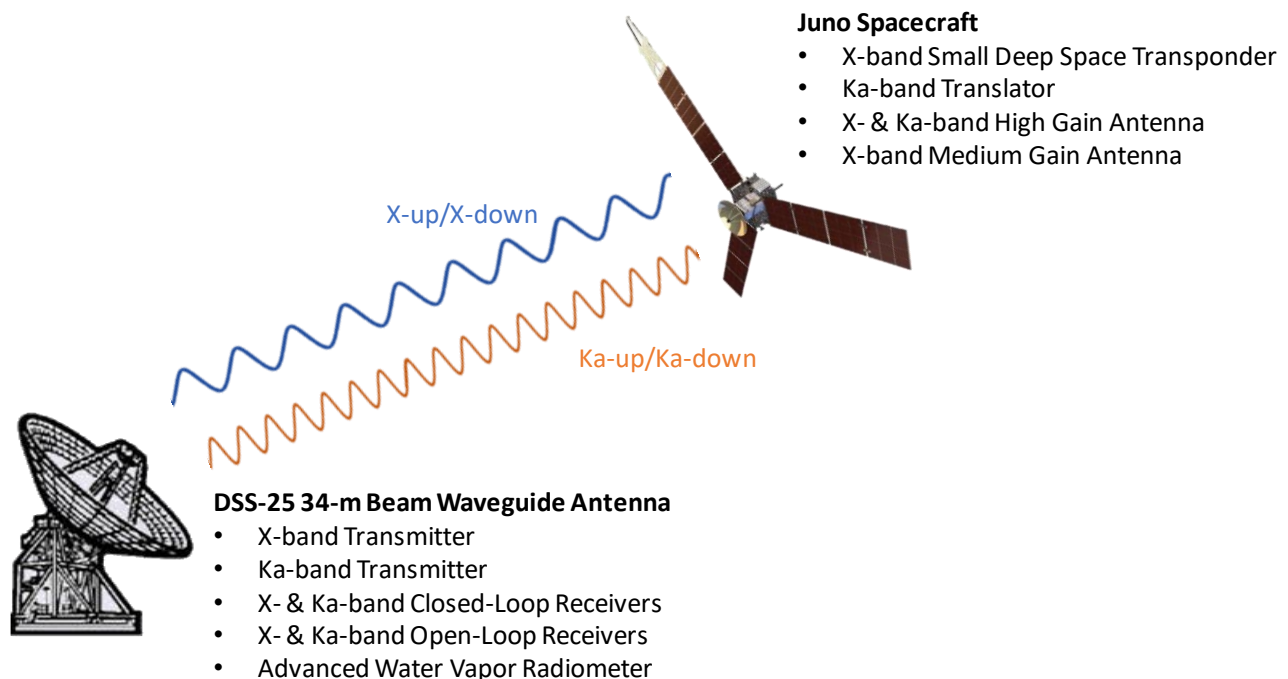


Figure 1. Overview of the Juno Gravity Science Instrument

antennas can be maintained more easily and can be modified more readily for new technologies. For example, the BWGs are capable of the simultaneous X-Band and Ka-Band reception needed for Juno gravity science [3].

One of the beam waveguide antennas, Deep Space Station 25 (DSS-25), had a new Ka-Band transmitter installed in 2015, making it the only station capable of transmitting two different bands, X-band and Ka-band, at the same time. A new transmitter delivered in 2015 has a power output of 300 W [3].

In addition, an Advanced Water Vapor Radiometer (AWVR) is located adjacent to DSS-25. The AWVR points along parallel to DSS-25 to the same position in the sky and takes measurements of atmospheric water vapor. These measurements are used to calibrate atmospheric effects which delay the transmission of the signal as it passes through the Earth's troposphere.

When the DSN transmits to Juno or any spacecraft, the frequency of the signal is shifted, due to the Doppler effect caused by the motion of the spacecraft relative to the antenna. In order for the spacecraft to lock onto the uplink, ramps in frequency are applied to the uplink to compensate for the Doppler shift, resulting in a more stable frequency being received by the spacecraft. Similarly, the Doppler shift is applied via frequency “predicts” in the ground receivers to tune to the frequency of the signal expected on the ground. Tuning of the uplink and downlink in this fashion normalizes the frequency data collected and used for gravity science.

3. CONSIDERATIONS IN 53-DAY ORBIT

After the decision to remain in the 53-day orbit was made [1], a new reference trajectory was created by the Juno navigation

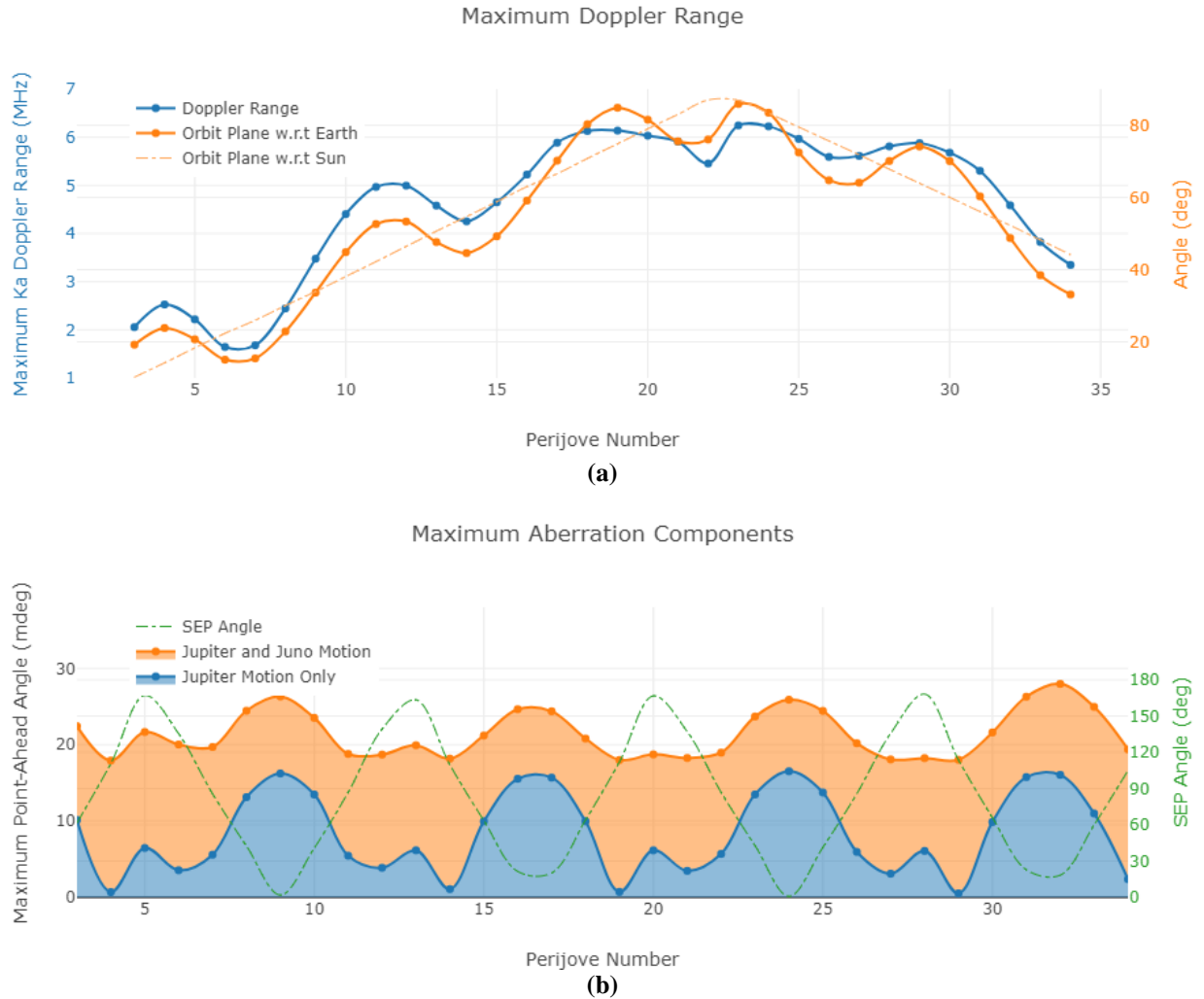


Figure 2. Maximum Doppler range (a) and maximum aberration point-ahead angle (b) for Juno perijoves in the 53-day orbit period. Variations in maximum Doppler range are largely driven by the orbit plane angle (β) while variations in the aberration point-ahead angle are driven by the Sun-Earth-Probe (SEP) angle.

team referred to as the 170320 trajectory [5]. This trajectory was analyzed to determine the impact to the operations of the Gravity Science Instrument. Two important items must be considered at Jupiter for radio science data acquisition: the Doppler dynamics and the aberration angle.

The Doppler dynamics, primarily the Doppler range, must be considered because the DSN applies Doppler compensation on both the uplink and downlink (Section 2). Since the Doppler measures the velocity of the spacecraft along the line of sight and Juno undergoes significant velocity changes due to the altitude at closest approach (~ 60 km/sec), a Ka-band Doppler range of 1.5-6.25 MHz is experienced at perijove. This changes as a function of perijove (Figure 2a) due to the angle between the orbit plane normal and the line-of-sight to Earth (β -angle). In the 53-day orbit, the orbit normal angle becomes nearly perpendicular to the line-of-sight ($\beta \approx 90^\circ$), projecting larger amounts of spacecraft velocity onto the Doppler signal. However, for the same reason the higher β -angle also improves the sensitivity of the gravity field.

A second consideration is the aberration angle, which is defined as the angle between the apparent downlink position (the position where the spacecraft was a light-time earlier) and the apparent uplink position (the position where the spacecraft will be a light-time later) as observed by the ground station. DSS-25 is able to compensate for the aberration by up to 30 millidegrees through a separate motion of the transmitter relative to the sub-reflector [3], and a test was required to ensure proper operation at the high aberration angle. The aberration angle increases when Juno is near solar conjunction, i.e. the farthest distance between Earth and Jupiter. Although Juno would not experience conjunctions in the shorter 14-day orbit, in the 53-day orbit there are four conjunctions, leading to four maximums in aberration angle on PJ-09, PJ-16, PJ-24 and PJ-32 (Figure 2b).

4. OPERATIONS SUMMARY

Up to September 2017, a total of eight perijove passes have been executed. A summary of each perijove from the context of the Gravity Science Instrument are shown in Table 1 and the operations described are briefly in this section.

Perijove PJ-01

Juno's first perijove pass occurred on August 27, 2016. This perijove occurred between the first two orbits in the GRAV orientation (Earth-point). The Madrid complex of the DSN supported radio science and telemetry downlink. Although the trajectory is designed around perijoves occurring over the Goldstone complex, the first perijove was not considered a science perijove as it would have originally been prior to the PRM maneuver. Because no Ka-band uplink is available at Madrid, the spacecraft was sequenced using the SDST-Ka band exciter for an X-up/X-down and X-up/Ka-down configuration with DSS-55 as the prime transmitting and receiving antenna. All remaining antennas at the Madrid complex (DSS-54, DSS-63, and DSS-65) provided higher signal-to-noise ratio for high-rate telemetry on the X-band

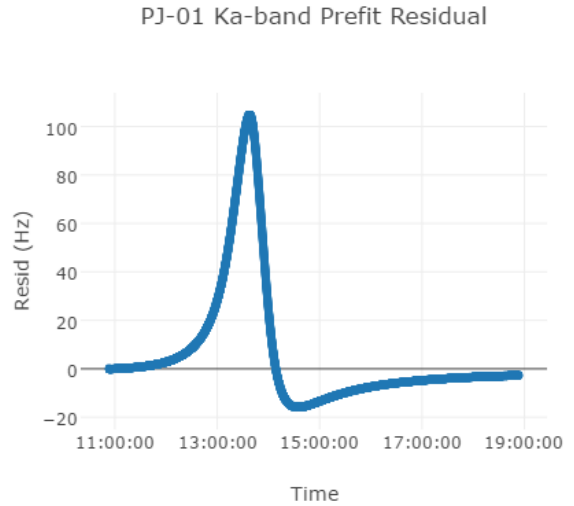


Figure 3. X-up/Ka-down prefit residuals during PJ-01 over DSS-55. A majority of the residual is due to trajectory, but the gravity signature due to Jupiter's gravitational field is also present.

signal. Perijove occurred at 13:44 UTC Earth Received Time (ERT).

All radio science data were collected as planned. The residual frequency (recorded value, or prefit) maximized at approximately 100 Hz in Ka-band shortly after closest approach, within the narrowest bandwidth of 1 kHz on the open-loop residual. The remaining residual is primarily error in the predicted trajectory; however, signatures due to gravitational field and pole of Jupiter are also present.

Perijove PJ-02

Since successfully entering into orbit and collecting science data during PJ-01, it was originally planned to conduct the Period Reduction Maneuver (PRM) during the second perijove on October 19, 2016, to reduce the orbital period from 53.5-days to 14-days. However, a risk identified in the propulsion system was discovered just prior to PRM, and the maneuver was cancelled. Investigation into the cause is ongoing.

In place of PRM, a contingency sequence was activated onboard the spacecraft to conduct a science perijove pass in place of the maneuver. The sequence enabled Ka-band onboard the spacecraft, for a dual X- & Ka-band link over DSS-25 around perijove. Approximately 13 hours prior to perijove, the spacecraft entered safe mode. Spacecraft fault protection disabled all instruments, including the KaT, and thus no Ka-band Doppler data were acquired during perijove. DSS-25 was released from the tracking schedule and the nearby DSS-26 antenna was utilized instead for coherent X-band data. These data can be used for gravity field determination, and thus the Gravity Science Instrument was the only instrument onboard that collected data during PJ-02.

Table 1. Summary of Gravity Science data collection during Juno perijoves as of September 2017

PJ Number	Date (UTC)	Spacecraft Orientation	Spacecraft Antenna	DSN Station	Frequency (uplink/downlink)
PJ-01	August 27, 2016	GRAV	HGA	DSS-54 DSS-55 DSS-63 DSS-65	X/X X/Ka
PJ-02	October 19, 2016	GRAV*	HGA	DSS-26	X/X
PJ-03	December 11, 2016	GRAV	HGA	DSS-14 DSS-25	X/X Ka/Ka
PJ-04	February 2, 2017	MWR	MGA	DSS-25	X/X
PJ-05	March 27, 2017	MWR-tilt	MGA	DSS-14 DSS-25	X/X
PJ-06	May 19, 2017	GRAV	HGA	DSS-14 DSS-25	X/X Ka/Ka
PJ-07	July 10, 2017	MWR	MGA	DSS-15 DSS-24 DSS-25 DSS-26	X/X
PJ-08	September 1, 2017	GRAV	HGA	DSS-14 DSS-25	X/X Ka/Ka

*The spacecraft entered safe mode prior to PJ-02 and Ka-band was disabled as part of the fault protection

Perijove PJ-03

The third perijove, PJ-03, occurred on December 11, 2016, at Earth-point in the Gravity Science orientation over DSS-25. This was the first use of dual X- & Ka-band links for gravity science estimation. The AWVR was running concurrently alongside the Doppler data collection to calibrate troposphere effects. This event was the first successful collection using the full configuration of the gravity science instrument and provides high quality data for the gravity science investigation. DSS-14 was configured in a downlink-only mode to listen to the X-band signal for high-rate telemetry.

Perijove PJ-04

The Juno Perijove 04 (PJ-04) Gravity Science activity was conducted in the Microwave Radiometer (MWR) attitude. In this orientation, the spacecraft pointed the MWR instrument nadir to the surface of Jupiter, and the High Gain Antenna (HGA) was off-Earth point by 23.9 degrees. Closest approach for PJ-04 occurred at 14:40 UTC (ERT). During PJ-04, Radio Science utilized the Medium Gain Antenna (MGA) onboard the Juno spacecraft to collect X-band Doppler measurements at DSS-25. Ranging and telemetry were off to optimize the received signal-to-noise ratio of the X-Band signal for gravity science.

During PJ-04, the average signal-to-noise ratio received was 10.7 dB-Hz and fluctuating due to asymmetries in the beam pattern. Since the minimum threshold for detection on the

DSN's closed-loop receiver is ≈ 10 dB-Hz [3], only the open-loop receivers were able to detect the signal on the MGA.

The physical location of the MGA is offset from the HGA [2]. Since Juno spins at approximately 2 RPM, the motion of the antenna relative to the spacecraft center of mass induces a Doppler effect onto the signal. This signature, observed previously (e.g. during Jupiter Orbit Insertion), was present during PJ-04 as shown in Figure 4.

Perijove PJ-05

The fifth perijove was conducted in the MWR attitude, but with the addition of a slight "tilt" to compensate for Jupiter's spin. Again, the MGA was utilized to collect coherent X-band data throughout the perijove. Closest approach occurred at 09:29 UTC (ERT). The addition of the "tilt" and higher β -angle (Figure 2a) increased the total off-Earth angle to 27.0 degrees, further stressing the link margin on the MGA. Because the link signal-to-noise ratio during PJ-04 was near threshold of the closed-loop receiver, the 70-meter DSS-14 antenna was added to listen for the signal during PJ-05 and provide backup.

DSS-25 provided initial uplink to the spacecraft (DSS-25 was chosen to uplink as the prime antenna due to the proximity of the AWVR media calibration unit), but the spacecraft did not acquire lock onto the uplink signal due to the poor uplink margin. In a quick turnaround, DSS-14, with an additional 6 dB of uplink power due to the larger aperture size, initiated

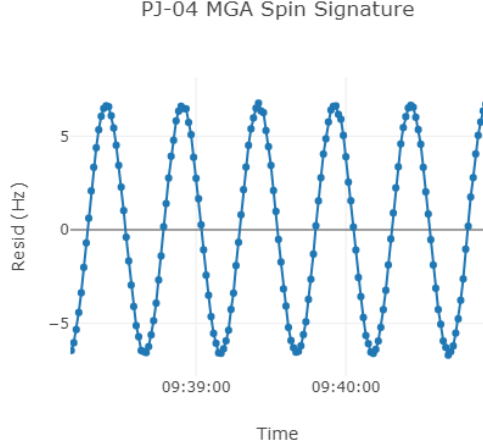


Figure 4. Residual frequencies observed during PJ-04, which is the spin signature of the MGA. The amplitude is approximately 13 Hz peak-to-peak and has a period of ≈ 0.033 Hz, corresponding the 2 RPM spin of the spacecraft.

uplink and acquired lock a round-trip light-time later. Coherent X-band data were then acquired throughout perijove at DSS-14 instead.

Perijove PJ-06

PJ-06 was the second use of dual X- and Ka-band links to determine Jupiter gravitational field parameters. The closest approach of PJ-06 occurred at 06:39 UTC (ERT). DSS-25 provided the uplink at X- and Ka-band and received the coherent downlink signals as expected. DSS-14 was utilized for X-band telemetry downlink only support.

Perijove PJ-07

PJ-07 was conducted in the MWR attitude. In addition to a standard perijove, Juno flew directly above the Great Red Spot during this perijove, looking for any atmospheric or interior signatures caused by the large storm.

The spacecraft was transmitting and receiving at X-band carrier only signals through the Medium Gain Antenna (MGA). However, the lack of a “tilt” and improved β -angle (Figure 2a) due to the location of Earth relative to Jupiter greatly improved the link margin since the total off-Earth angle was only 16.0 degrees. Juno successfully locked onto DSS-25’s uplink signal and DSS-25 was able to lock to the downlink signal throughout the perijove, collecting coherent X-band data for gravity science measurements.

During the time of PJ-07, the 70-m DSS-14 antenna, crucial for support of PJ-05, was down for maintenance. DSS-15, DSS-24, DSS-25, and DSS-26 were instead configured into an array to provide a similar increase in signal-to-noise ratio.

Perijove PJ-08

The PJ-08 pass of Jupiter was again a repeat of the GRAV orientation over Goldstone. This was the third time that dual coherent X- and Ka-band links were utilized to investigate the gravitational field of Jupiter. Perijove occurred at 22:40 UTC (ERT), with DSS-25 providing the prime uplink and downlink gravity science observables. DSS-14 again listened in to decode high-rate telemetry at X-band. All data were collected as planned.

5. RESULTS FROM THE GRAVITY INVESTIGATION

Gravity Field

The Juno gravity science data collected have been analyzed and published to produce gravity field solutions [6] [7]. Planetary gravity fields are typically represented by a spherical harmonic expansion of the gravitational potential U as a function of radius r , latitude ϕ , and longitude λ [8]:

$$U = \frac{\mu}{r} - \frac{\mu^*}{r} \sum_{l=1}^{\infty} \left(\frac{a_e}{r}\right)^l P_l(\sin \phi) J_l + \frac{\mu^*}{r} \sum_{l=1}^{\infty} \sum_{m=1}^{\infty} \left(\frac{a_e}{r}\right)^l P_{lm}(\sin \phi) [C_{lm} \cos m\lambda + S_{lm} \sin m\lambda] \quad (1)$$

Where μ is the gravitational parameter, a_e is the reference radius (for Jupiter, $a_e = 71,492$ km) and P_{lm} is the Legendre polynomial. The coefficients J_l represent the zonal harmonics (independent of longitude). The coefficients C_{lm} and S_{lm} represent the tesseral and sectoral harmonics. A gravity field solution is produced by fitting the Doppler observables through a Kalman filter to solve for the gravity coefficients.

Folkner et al. 2017 [7] analyzed the first two perijove passes (PJ-01 and PJ-02) to provide the first solution of the gravity field. Due to Juno’s orbit geometry, even with only two perijove passes, the precision of the gravity field has improved over previous missions (Pioneer flybys, Voyager flybys, Galileo orbiter, Cassini flyby, and New Horizons flyby) by a factor of five or more [7]. The low-degree zonal harmonics up to degree 8 were estimated along with a degree-two tesseral field and Jupiter’s spin axis direction (right ascension α and declination δ). The odd zonal harmonics (J_3 , J_5 , etc) were not statistically significant based on the first two perijoves.

Constraints on the Interior

If a planet is spinning and in hydrostatic equilibrium, the even zonal harmonics (i.e. J_2 , J_4 , J_6 , ...) are directly related to the internal mass distribution [8]. The precision of the even gravity coefficients measured by Juno in the first two orbits is sufficient to provide constraints on the interior models.

The reference model of the interior, prior to Juno's arrival at Jupiter, proposes a core composed of heavy elements (those elements with a greater density than helium) at the center of Jupiter surrounded by a region of primarily metallic hydrogen. A third, outermost layer composed of molecular hydrogen surrounds the inner two layers [9].

The reference model for Jupiter's interior, prior to Juno's arrival at Jupiter, is not compatible with the observations of the even zonal harmonic coefficients [10]. Wahl et al. 2017 [10] proposed a series of models with a diluted core of approximately 0.3-0.5 times the radius of Jupiter where the heavy elements are dissolved into the metallic hydrogen layer. The diluted core helps fit the observations of the even zonal harmonics. Improvements to the higher-order even zonal harmonics (e.g. J_6 , J_8) from future perijove passes may further constrain the set of allowable interior models.

6. CONCLUSION

Since entering orbit around Jupiter on July 4, 2016, and September 2017, the Juno spacecraft has executed eight perijove passes. For each of these passes, the Gravity Science Instrument has collected valuable Doppler data between the Deep Space Network and the Juno spacecraft to provide constraints on the interior of Jupiter. Despite issues during PJ-02, where the spacecraft entered safe mode, and on PJ-05, where the initial uplink did not get into the spacecraft, the robustness of the Deep Space Network and configuration of the Gravity Science Instrument nonetheless allowed for successful data collection for every perijove.

Key lessons were learned during initial orbital operations that have continued to be applied to Juno but also can apply to future missions with radio science investigations. First, "test-as-you-fly" instrument practice tracks allowed for issues and idiosyncrasies to be ironed out before science data collection leading to successful perijoves. Second, a robust DSN configuration allowed for real-time changes leading to successful experiments. For example, the addition of DSS-14 to the tracking passes ensured a successful PJ-05 track, where DSS-25 could not close the link due to uncertainties in the spacecraft antenna pattern. Third, the adaptable instrument configuration to meet various mission geometries allowed for a quick turnaround when the Period Reduction Maneuver was cancelled and a new 53-day orbit mission developed.

Analysis of the Gravity Science data at Jupiter has yielded a major improvement in the gravitational field parameters, up to a factor of five when compared to previous missions. These new values provide key constraints on the interior, possibly leading to the adoption of a diluted core model for the interior of Jupiter. As the Juno mission progresses, future perijove passes will have a larger Doppler signature projected onto the Earth-line, further improving the knowledge of Jupiter's gravitational field.

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BIOGRAPHY



Dustin Buccino is a member of the Radio Science Systems Group at NASA's Jet Propulsion Lab. Since joining the group in 2013, he has provided scientific and engineering support to the Cassini, Dawn, InSight, GRAIL, and Juno missions. His research interests include gravity science, navigation, and tracking of spacecraft. Buccino is currently the instrument operations lead for the Juno Gravity Science investigation.



Daniel Kahan is a senior member of the Radio Science Systems Group at NASA's Jet Propulsion Laboratory. He has provided engineering support for the radio science community on multiple NASA missions including Mars Global Surveyor, Mars Reconnaissance Orbiter, the GRAIL lunar mission, the International Cassini mission to Saturn, Mars Science Laboratory, and Juno.



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Kamal Oudrhiri is the manager of the Radio Science Systems Group at NASA's Jet Propulsion Laboratory and is currently the deputy project manager of the Cold Atom Laboratory. Oudrhiri has led multi-disciplinary teams through the design, implementation and delivery of flight hardware to the radio science community. Over the last decade, Oudrhiri served in key roles on multiple NASA missions.